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Visual Simulation S&T: Summary of Accomplishments

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14. ABSTRACT
The research performed under Task Order 24 of Air Force Contract F41624-97-D-5000 for the period 1 June 2002 through 30 November 2005 is summarized in this technical report. The summaries includes citations and associated abstracts of published research, as well as a more complete description of seven of the major research projects conducted as part of this Task Order.

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PREFACE

This research was conducted at the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HEA), Warfighter Training Research Division in Mesa, Arizona. This research is documented under Work Unit 1123-AE-01, Warfighter Training Research Support, under contract F41624-97-D-5000 to Link Simulation and Training, a division of L-3 Communications Corp.

The Laboratory Task Monitor was Dr. Byron J. Pierce, and the Laboratory Contract Monitor was Mr. M. Jay Carroll.

VISUAL SIMULATION S&T:
SUMMARY OF ACCOMPLISHMENTS

OVERVIEW

Over the past two years, the Air Force Research Laboratory, Human Effectiveness Directorate, Warfighter Readiness Research Division (AFRL/HEA) has continued research and development of new visual systems to enhance and support Distributed Mission Operations (DMO). Perceptual research has included projects to:

1. assess simulated target visibility as the relative detail of target and background is varied in out-the-window and targeting pod air-to-ground simulations;
2. determine the effects of depth-of-focus on the visibility of high-detail helmet-mounted-display (HMD) symbology used with out-the-window (OTW) imagery;
3. validate and apply techniques for quantifying the spatial and temporal properties of visual systems being considered for use in flight-simulator applications;
4. evaluate temporal requirements for liquid crystal-based displays for presentation of fast moving imagery;
5. determine the effects of visual occlusion on the ability of pilots to maintain their altitude;
6. determine factors contributing to temporal aliasing effects in high resolution display imagery and methods for mitigating those effects; and
7. determine ranges for identification of aircraft aspect, and detection of aircraft roll, for simulated air-to-air targets at various levels of image-generator and display resolution.

Collaborative Research Projects

The perceptual research team supported development of high-resolution display technologies through:

1. identification of potential perceptual issues,
2. applied research to resolve those issues,
3. development and application of system test procedures,
4. participation at design reviews,
5. the writing of position papers and test plans, and
6. review of design proposals.

Consultation was provided to Air Force major command (MAJCOM) and procurement representatives on visual systems being considered for major weapon systems trainers (e.g., F-22 and Joint Strike Fighter [JSF]). We also consulted and worked with industrial partners on new visual systems technologies (e.g., Evans and Sutherland, Barco, VDC Inc, Boeing, L-3 Comm, Lockheed Martin, and CAE). We collaborated on an international program with the Defense Research and Development Canada (DRDC)–Toronto to develop laser light modulation technologies at the Institute of National Optics in Quebec City, Canada. We also worked with our visual engineering development team on several new display technologies being development under Small Business Innovative Research contracts.

University Educational Partnership Agreements

We performed collaborative research with visual and human factors scientists at several major universities, and in several research areas:

1. Washington State University (Psychology Department): Visual cues for heading maintenance in simulated flight and perceptual issues in helmet-mounted display design (National Research Council [NRC] Summer Faculty Fellowship Program, sub-contract consultant, and Educational Partnership Agreement [EPA]).
2. Arizona State University East (Psychology Department): Visual cues for altitude maintenance in simulated flight (Consulting agreement and EPA).
3. City College of New York (Computer Science Department): Analysis of image motion cues in simulated flight (EPA).
4. Harvard University (Schepens Eye Research Institute): Perceptual issues in helmet-mounted display design (EPA).
5. Virginia Commonwealth University: Eye-movement recording (EPA).
6. Texas Tech University (Psychology Department): Behavioral research, and development of simulation support technologies (EPA).

SUMMARIES OF MAJOR PERCEPTUAL RESEARCH

Peer-Reviewed Journals and Proceedings

**NOTE: The following documents summarize work accomplished and published in peer-reviewed journals, and proceedings of meetings/symposia during the period covered by Task Order 24 of AF Contract F41624-97-D-5000. Citations have been updated for the benefit and convenience of the reader.*

1. Chaudhry, S. & Geri, G.A. (2003). Display related effects of terrain-texture density and contrast on perceived airspeed in simulated flight. SID International Symposium, Baltimore, MD. *Society for Information Display Symposium Digest*, 23.

The display-dependent effects of both terrain texture density and contrast were assessed using a speed maintenance task in a high performance flight simulator. Density and contrast varied in opposite directions with simulated distance, and were found to have opposite effects on perceived speed. The functional range of the interaction between density and contrast was estimated.

2. Covas, C.M., Patterson, R, Geri, G.A., Akhtar, S.C., Pierce, B.J. & Dyre, B.P. (2005). Horizontal motion-parallax is as effective as texture density for altitude control in simulated flight. SID International Symposium, Boston, MA. *Society for Information Display Symposium Digest*, 25, 382-385.

Terrain and 3D-object properties were varied in order to assess the effects of horizontal motion-parallax on altitude control. For 3D objects alone, performance was equivalent to that found with real-world terrain texture, suggesting a difference in the role of horizontal and vertical motion-parallax cues in simulated-aircraft control.

3. Geri, G.A., Akhtar, S.C. & Pierce, B.J. (2004). Spatial frequency correlates of perceived temporal aliasing in simulated real-world imagery. In Proceedings of the European Conference on Visual Perception, Budapest, Hungary. *Perception*, 33 (Supplement), 165.

We have compared the spectral characteristics of simulated imagery with the appearance of spatiotemporal aliasing to establish the practical limitations on the visual cues required to simulate motion over complex terrains. Imagery was produced by a personal computer (PC), and displayed in the front channel (55 deg x 50 deg) of an operational jet craft flight simulator. Observers flew passively over a low-pass random noise texture (4 texture elements/m^2 at an altitude of 30 and speeds of between 50 and 500 m s^{-1}. They were asked to indicate the farthest location on the database where the simulated image motion became either discontinuous or incoherent. Owning primarily to image perspective, the vertical spectra (V) were generally flatter than the horizontal spectra (H) (mean values were V: $1/f = 1.41$ and H: $1/f = 1.11$). The pattern of perceived image coherence coincided with image spatial frequencies in the range of 0.5 – 2.0 cycles/deg, indicating that the perception of self-motion can be mediated by restricted portions of a wide-field image, although these lower frequencies may not provide robust cues to motion. In addition, the presence of motion incoherence, mostly in the visual periphery, did not significantly affect the perception of self-motion.

4. Geri, G.A., Akhtar, S.C. & Pierce, B.J. (2005). Identification of simulated targets as a function of target and background blur. SID International Symposium, Boston, MA. *Society for Information Display Symposium Digest*, 25, 394-397.

Simulated imagery was used to determine the effect of target and background blur on target identification performance. An interaction between these two variables was found, indicating that greater image detail may not improve performance, and hence may not be required in applications for which high-resolution databases are not readily available.

5. Geri, G.A., Covas, C., Winterbottom, M.D., & Pierce, B.J. (2005). Accurately representing target distance in a flight simulator. In *Proceedings of the Interservice/Industry Training, Simulation and Education Conference.* Orlando, FL.

Rendering an essentially continuous image generator (IG) image onto the discrete-pixel array of most display devices, as well as graphical processing such as antialias filtering, can result in significant variations in displayed target size and hence simulated distance. Using videotape recordings obtained from a cathode ray tube (CRT)-based, flight-simulator display, we have directly measured changes in size, over a three-second simulation interval, of target aircraft simulated at distances between 3,000 and 11,000 feet. In Experiment 1, the percentile of the measured target-size distribution which corresponded to the nominal target size was found to change with simulated distance. Additionally, an interaction was found between pixel count (1280 × 1024 and 2048 ×1536) and antialias filtering (0 and 2×). In Experiment 2, a single intermediate pixel count (1600 × 1200) was tested, and in addition, eight target gray-levels were tested perceptually, to directly compare the videotaped imagery with what was visible on the screen. It was found that the percentile corresponding to nominal target size varied with both simulated distance and antialiasing condition (0 and 4×). In both experiments, for the larger (i.e., closer) targets, the nominal target size corresponded to about the 96th percentile of the distribution of measured sizes. As target size was decreased, nominal size was found to correspond to as low as the 60th percentile. Further, in both experiments, the functions relating the relevant size-distribution percentiles to simulated distance were nonlinear, and in Experiment 2 they were different for each of the antialiasing conditions tested. The data indicate that the average size of targets displayed in CRT-based flight simulators is smaller than would be expected from their nominal distance as defined by the IG. In addition, the unexpected complexities found in the size-distribution data indicate that accurately adjusting displayed target size to reflect a chosen target distance will require corrections that are dependent on simulated distance.

6. Geri, G. A. & Winterbottom, M. D. (2005). Effect of display resolution and antialiasing on the discrimination of simulated-aircraft orientation. *Displays*, 26, 159-169.

In Experiment 1, antialiasing was found to improve performance on an orientation-discrimination task, whereas increasing display pixel-count did not. This was attributed to a decrease in image contrast associated with driving the CRT beyond its effective bandwidth. In Experiment 2, it was found that display resolution is the primary determinant of orientation-discrimination performance. This performance was not significantly improved by increasing antialiasing beyond a minimal level, suggesting that greater image detail can be substituted for antialias filtering. Finally, data obtained from an objective target-size calibration showed that nominal target size often does not accurately reflect the size (and hence distance) of simulated targets

7. Gray, R., Geri, G., Akhtar, S., & Covas, C. (2004). The contribution of 3-D object height and density to altitude maintenance in low-altitude flight. Visual Sciences Society. *Journal of Vision*, *4(8)*, 843.

Previous research has shown that pilots can regulate altitude using various visual cues. We investigated the effects and interaction of 3-D object height and density on altitude maintenance in low-altitude flight. Six observers attempted to maintain an initial altitude of 30 m during simulated flight over a simulated image consisting of undulating grey terrain and 3-D objects (trees). The tested tree heights and densities were 2.5, 5, 10, and 20 m, and 0.25, 1, 2, 4, and 64 trees/km^2, respectively. Flight at 232 m/sec (450 knots) was simulated using a high-performance PC-based image generator (MetaVR Inc.). The visual scene consisted of three, rear-projected, 1600 × 1200 images that together subtended 180º H × 63º V. Auditory feedback was presented if observers flew $\pm$10 m from the initial 30 m altitude. Results showed that the RMS error was strongly related to the product of tree height and tree density (R^2 values ranged from 0.7-0.86). On a practical level, there appears to be a trade-off between object height and density in display design (e.g., good flight performance in a low density display can be achieved with taller objects). On a theoretical level, the results suggest that observers estimated altitude using a higher order visual cue that is a combination of height and density cues.

8. Lindholm, J.M., Scharine A., & Pierce, B.J. (2003). Motion quality in simulator imagery: Some effects of resolution. In *Proceedings of the Interservice/Industry Training, Simulation and Education Conference*. Orlando, FL.

The level of detail in flight-simulator imagery depends upon the resolutions of the database, the IG, and the display. In response to the need for greater detail, resources are being devoted to increasing the spatial resolution of each of these system components. Next-generation flight-simulator visual systems will thus be capable of representing smaller environmental features and of representing a given feature at a greater distance. However, flight-simulator imagery is more than a sequence of static, spatial images. During simulated flight, the system creates a three-dimensional (two dimensions of space, one of time) space-time image that approximates the continuous changes in the spatial image that would result if the pilot were to actually fly through the synthetic environment. The quality of such space-time images depends upon the temporal as well as the spatial characteristics of the IG and the display. We (a) discuss how database and IG resolutions and simulated-flight speed and altitude affect the temporal frequencies in an image and thus the extent of temporal aliasing likely in simulator imagery, (b) describe effects of a display system's spatial and temporal resolution on the spatiotemporal-frequency spectrum of a display image, (c) summarize characteristics of the human visual system relevant to spatiotemporal-frequency and motion perception, and (d) report preliminary results of a research project in which we are examining the effects of image resolution on perceived-motion quality during simulated flight.

9. Patterson, R, Akhtar, S.C., Geri, G.A., Morgan, W. & Pierce, B.J., Dyre, B.P., & Covas, C.M. (2004). Terrain texture and 3-D object cues in the control of heading in simulated flight. 34th Annual Meeting of SID International Symposium, Seattle, WA. *Society for Information Display Symposium Digest*, 24.

The effects of terrain texture type and the height and density of 3D objects on heading control were studied in two experiments conducted in a high-performance flight simulator. The results suggest an orthogonal-extension principle which relates performance to the number and length of contours that are perpendicular to the ground plane, and also begin to define the stimulus conditions for which the principle is valid.

10. Patterson, R., Geri, G.A., Dyre, B, Akhtar, S.A., Covas, C.M., Morgan, W. & Pierce, B.J. (2006). Active heading control in simulated flight based on vertically extended contours. *Perception and Psychophysics, 68(4),* 593-600.

In two experiments, we manipulated the properties of 3D objects and terrain texture to investigate their effects on active heading control during simulated flight. Simulated crosswinds were used to introduce a rotational component into the retinal flow field that presumably provided the visual cues used for heading control. An active control task was used so that the results could be generalized to real-world applications such as flight simulation. In Experiment 1, we examined the effects of three types of terrain, each of which was presented with and without 3D objects (trees), and found that the presence of 3D objects was more important than terrain texture for precise heading control. In Experiment 2, we investigated the effects of varying the height and density of 3D objects, and found that increasing 3D object density improved heading control, but that 3D object height had only a small effect. Based on these results, we conclude that the vertical contours improved active heading control by enhancing the motion parallax information contained in the retinal flow.

11. Patterson, R., Geri, G.A., Dyre, B. Akhtar, S., Covas, C. & Pierce, B.J. (2005). Altitude control in simulated flight using 3-D objects and terrain texture. *Journal of the Society for Information Display,* **13**, 1039-1044.

In this study, we investigated the effects of manipulating the properties of 3D objects and terrain texture on the control of altitude in simulated flight. We found that 3D objects were as effective as terrain texture for controlling altitude, and interpreted this result as suggesting that both terrain texture and 3D objects can serve as effective carriers of information about motion parallax and optical expansion and contraction. The present results, which were obtained using a vertically defined flight task, are inconsistent with the findings of Patterson et al.[11], who reported that 3D objects were more effective than terrain texture for controlling a horizontally defined heading task. The present results indicate that, when terrain texture is present, the motion parallax or optical expansion associated with the presence of 3D objects does not improve altitude control.

12. Patterson, R., Winterbottom, M., & Pierce, B. (2006). Perceptual issues in the use of head-mounted displays. *Journal of the Human Factors and Ergonomics Society, 8(3),* 555-573.

This journal article provides a review and analysis of much of the published literature on visual perception issues that may impact the design and use of HMDs. In doing so, this review also draws heavily from the basic vision literature to help provide insight for future design solutions for HMDs. In particular, we discuss several key perceptual issues that are relevant to the use of HMDs. The issues discussed are: (a) brightness and contrast and their effect on depth of field, dark focus and dark vergence, and perceptual constancy; (b) accommodation-vergence synergy and its effect on perceptual constancy, eyestrain and discomfort; (c) field of view and its relationship to the functioning of different visual pathways and the types of visual-motor tasks mediated by them; (d) binocular input and its relationship to visual suppression (i.e., binocular rivalry); and (e) head movements and the importance of head tracking and display update lag. This article concludes with a set of recommendations for the design and use of HMDs.

13. Winterbottom, M.D., Geri, G.A., Morgan, W., & Pierce, B.J. (2004). An integrated procedure for measuring the spatial and temporal resolution of visual displays. In *Proceedings of the Interservice/Industry Training, Simulation and Education Conference*. Orlando, FL.

Spatial and temporal resolutions are two of the most fundamental characteristics of visual displays, and yet they are often incorrectly defined and specified. To address this problem, we have developed techniques for estimating both spatial and temporal resolution, and we have compared the resulting estimates to data obtained from perceptual tasks. The spatial resolution technique is based on a Video Electronics Standards Association (VESA) standard (Flat Panel Display Measurement [FPDM], Ver. 2.0), and was applied to several CRT displays. It was found that the pixel count does not adequately define display resolution when the former exceeds the bandwidth of the display device. In addition, the spatial resolution measurements were found to correlate well with perceptual assessments of the orientation of target aircraft simulated at various distances. The temporal resolution technique involved measuring the response of various displays to simple light patterns that could be flickered at up to 30 Hz. Data obtained for CRT projectors indicated that temporal artifacts obtained with these devices are due primarily to the limited frame rate of the image generator, rather than to limitations in the temporal response of the projectors. In addition, data obtained from liquid crystal on silicon (LCoS) projectors indicated that their on- and off-responses are short enough to support 60 Hz simulator frame rates, but that the hold-time used to maximize image luminance interacts with eye movements to produce temporal artifacts that can reduce the quality of the displayed imagery. The results of a perceptual test, based on the perceived separation of moving lines, were consistent with the measured temporal resolution of the two displays.

14. Winterbottom, M.D., Geri, G.A. & Pierce, B.J. (2003). Effect of display line rate and antialiasing on the recognition of aircraft aspect angle. SID International Symposium, Baltimore, MD. *Society for Information Display Symposium Digest, 23.*

Increasing display line rate did not improve aspect-angle recognition performance beyond a level predicted by measured display resolution. Image antialiasing improved performance even though it did not increase the measured spatial resolution. Finally, the threshold for aspect-angle recognition was found to be consistent with that obtained for other visual tasks dependent on target spatial detail.

15. Winterbottom, M.D., Patterson, R., Pierce, B.J., Covas, C. & Winner, J. (2005). Depth of focus and perceived blurring of simultaneously-viewed visual displays. In *Proceedings of Interservice/Industry Training, Simulation and Education Conference*. Orlando, FL.

HMDs have not previously been combined with flat-panel display systems and it was unknown whether viewing two displays at differing focal plane distances would lead to perceived blurring or visual discomfort. This is now a concern as the Joint Helmet Mounted Cueing System (JHMCS) is integrated with existing flat-panel display systems such as the

Mobile Modular Display for Advanced Research and Training (M2DART). The degree of blurring that could occur would be dependent upon observers' depth of focus and the extent to which the two displays vary in focal plane distance. In previous research, we investigated whether blurring occurs when two displays are viewed simultaneously at independently varying focal plane distances. These conditions simulated those of a monocular HMD integrated with the M2DART. The results of that research suggested that blurring due to two differing focal planes was not likely to be a significant issue for the current configuration of the M2DART. We present here two additional experiments that extend these earlier results. In the first experiment, luminance levels were decreased, thus increasing pupil size and decreasing depth of focus and the degree of blurring was measured using psychophysical techniques. In the second experiment, blurring and visual discomfort were examined under more typical viewing conditions: observers performed a task similar to off-bore sight targeting in the M2DART using a monocular HMD. They identified the orientation of an aircraft target presented on the M2DART and a test letter presented on the HMD. Assessments of eyestrain and perceived blur were obtained during the performance of this task. The results of these two experiments indicated that depth of focus should not be an issue for standard-resolution displays and, further, that visual discomfort is not likely to be an issue for the integration of a monocular HMD with the M2DART.

16. Winterbottom M.D., Patterson, R, Pierce, B.J., Covas, C., & Winner, J. (2005). The influence of depth of focus on visibility of monocular head-mounted display symbology in simulation and training applications. In *Proceedings of the SPIE Defense & Security Symposium*. Orlando, FL

The JHMCS is being considered for integration into the F-15, F-16, and F-18 aircraft. If this integration occurs, similar monocular HMDs will need to be integrated with existing out-the-window simulator systems for training purposes. One such system is the M2DART, which is constructed with flat-panel rear-projection screens around a nominal eye-point. Because the panels are flat, the distance from the eye point to the display screen varies depending upon the location on the screen to which the observer is directing fixation. Variation in focal distance may create visibility problems for either the HMD symbology or the out-the-window imagery presented on the simulator rear-projection display screen because observers may not be able to focus both sets of images simultaneously. The extent to which blurring occurs will depend upon the difference between the focal planes of the simulator display and HMD as well as the depth of focus of the observer. In our psychophysical study, we investigated whether significant blurring occurs as a result of such differences in focal distances and established an optimal focal distance for an HMD which would minimize blurring for a range of focal distances representative of the M2DART. Our data suggest that blurring of symbology due to differing focal planes is not a significant issue within the range of distances tested and that the optimal focal distance for an HMD is the optical midpoint between the near and far rear-projection screen distances.

Technical Reports and Technical Memos

**NOTE: The following documents summarize work accomplished and published during the period covered by Task Order 24 of AF Contract F41624-97-D-5000. Citations have been updated for the benefit and convenience of the reader.*

1. Geri, G.A., & Akhtar, S.C. (2004). Flight-simulator performance evaluation using a low-altitude flight task. (Contractor prepared technical report, AF Contract F41624-97-D-5000 Task Order #24). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

The functional limitation of current, jet aircraft flight simulators is most evident at low altitudes where image detail varies rapidly. Two primary sources of image detail in low-altitude flight (LAF) are the density of the ground texture and the number of 3-D objects. Thus, a flight simulator can be evaluated based on the performance of a pilot on LAF tasks which are dependent upon texture density and 3-D object cues. Further, such performance data may be used to specify the minimum requirements for texture density and 3-D object density in the simulation of low-altitude flight. We have attempted to quantify, and hence evaluate, simulator performance by measuring the RMS error associated with altitude maintenance during LAF. In Experiment 1 we used a simple, low-pass noise texture whose density was either 2.4×10^{-4}, 1, or 4096 elements/m^2, and found, contrary to general expectation, that RMS error increased as texture density increased. In Experiment 2, we varied the number of 3-D objects between 0.025 and 256 objects/km^2, and found that error decreased roughly exponentially as object density was increased. In Experiment 3 we attempted to relate the data of Experiment 1 to analogous data obtained during LAF over a simulated real-world database, and found that RMS error was approximately equal for our 1 elements/m^2 low-pass noise data and the real-world terrain. The spectral data may also be useful for determining the relative effects of spatial frequency content and image contrast on altitude maintenance performance. Finally, we have compared the spectral properties of our low-pass noise and real-world textures to verify their similarity, and as a first step in establishing that relatively simple and easily specifiable textures are adequate approximations of more complex real-world textures, and so may potentially be used as generic textures when evaluating simulators used in variety of a applications that require diverse types of terrain databases.

2. Geri, G.A., & Akhtar, S.C. (2004). Individual differences in the effect of texture density and contrast on speed maintenance in simulated flight. (Contractor prepared technical report, AF Contract F41624-97-D-5000, Task Order #24). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

The presence of two-dimensional patterns enhances the detection of changes in speed during low-altitude flight (LAF). The display-dependent effects of both terrain texture density and contrast were assessed using a speed maintenance task in a high performance flight simulator. Previous studies have found that perceived speed may either increase or decrease as texture density is increased. Perceived speed is also affected by the contrast of the texture pattern used to evaluate it. Density and contrast varied in opposite directions with simulated distance, and were found to have opposite effects on perceived speed with individual differences. The present study is an attempt to further investigate those individual differences. If those differences represent a different perception of the speed of moving simulator imagery, they may have implications for both simulator training and simulator database design.

3. Geri, G.A. & Akhtar, S.C. (2004). Performance benchmarks for flight-simulator image generation: A preliminary investigation (AFRL-HE-AZ-TR-2004-0082, AD B326048). Mesa, AZ: Air Force Research Laboratory, Warfighter Training Research Division.

We describe here two benchmark tests that may be used as part of a larger benchmarking system to assess the performance of PC-based, flight-simulator IGs. The tests are based on the changes in update rate associated with changes in the number of rendered triangles in the visual scene. The number of triangles was varied by simulating low-altitude flight over a database of fixed size. Preliminary results indicate that, for maintaining a specified update rate, the total number of terrain triangles interacts with how they are grouped for the purpose of retrieving them from memory. Further, triangles associated with 3-D objects are processed more slowly than those associated with the terrain height map. These results demonstrate the importance of both using a diverse set of benchmark tests and taking into consideration the specific database generation and run-time techniques used by a particular IG system. Finally, we discuss some issues involved in increasing the generality and utility of benchmark tests like those described here.

4. Geri, G., Caufield, K., & Winterbottom, M. (2006). The variability of spatial resolution estimates obtained using a CCD camera (AFRL-HE-AZ-TM-2006-0003, ADA462516). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

We previously developed techniques for measuring the spatial resolution of flight simulator displays. In this experiment, we estimate the relative variability of the measurement technique and the display projectors they were designed to assess. We used the ratio of the standard deviation and mean of the resolution estimates as a measure of variability. Variability was found to be about 1.3% for grating transparencies illuminated by a stable light source. This value may be taken as the inherent variability of our measurement hardware and analysis procedures. Analogous measurements made on CRT projectors resulted in a mean variability of about 4.3%. The difference between the two estimates, 3.0%, may be taken as a measure of the variability of the CRT projectors alone.

5. Geri, G.A. & Morgan, W.D. (2006.) A comparison of the temporal characteristics of LCD, LCoS, laser, and CRT projectors (AFRL-HE-AZ-TM-2006-0001, ADA462549). Mesa AZ: Air Force Research Laboratory, Human Effectiveness Directorate, Warfighter Readiness Research Division.

We have measured the temporal response of a commercial LCoS projector, and have compared it to that of commercial LCD and CRT projectors, as well as to a prototype laser projector. The faster temporal response of LCoS displays, as compared to more conventional LCDs, has not been considered a major factor in their commercial use, and so individual pixels are not turned on and off in these devices as quickly as the technology allows. Based on informal discussions with LCoS manufacturers and users, it appears that changes can be made in the LCoS display electronics to reduce pixel response times in order to sufficiently reduce smearing in moving simulator images.

6. Geri, G.A. &, Morgan, W.D. (2004). User's manual and circuit description for a photodiode/amplifier device designed to measure the temporal response of video displays

(*Warfighter-Contract Technical Memorandum 24-05*)**.** Mesa, AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

We present here a user's manual for a Photodiode/Amplifier (P/A) device that was designed to measure the temporal response of video displays. We also present a detailed description of, and rationale for, the components used in the photodiode and amplifier circuitry.

7. Geri, G. & Winterbottom, M. (2003). Brightness and spatial resolution of a prototype, green-laser projector measured for various display screens and image sizes (AFRL-HE-AZ-TM-2006-0002, ADA462491). Mesa, AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

There were no apparent difficulties or complications in measuring the luminance of the laser projector using a standard spotmeter. However, a laser-projector image judged to have the same brightness as a CRT image had a measured luminance that was about 14% less. Thus, the limited and preliminary data reported here indicate that a laser image of the same luminance appears slightly brighter than that of a CRT. There were some differences between the CRT and laser measurements made with a spotmeter and with a CCD photometer. Although the differences were relatively small for display luminances less than about 5 fL, this issue should be addressed further with future versions of the laser projector. There appears to be a real difference in the spatial resolution measured at the center and edge of imagery projected onto the three screen tested. However, given the variability of the measurements, there is no clear evidence of significant differences among the three screens tested in center-to-edge spatial resolution. The relatively small (5.5% overall) reduction in spatial resolution as projected image size was reduced represents an apparent advantage of the laser projector over other displays. Further data are needed, however, to determine if this reduction in spatial resolution is significantly greater at the edge of the image.

8. Geri, G.A. Winterbottom, M. & Pierce, B.J. (2004). Evaluating the spatial resolution of flight-simulator visual displays (AFRL-HE-AZ-TR-2004-0078, AD427971, ADM001720). Mesa AZ: Air Force Research Laboratory, Warfighter Training Research Division.

This paper documents a technique for assessing the spatial resolution of visual display systems like those currently used for flight simulation at AFRL, Mesa, AZ. The introduction defines spatial resolution and how best to apply the concept in the context of visual display evaluation. The measurement technique is described in detail, as are the CCD-based light measurement device and the techniques developed to calibrate it. Typical spatial resolution data are presented for a variety of display systems. The various steps required for data analysis, and suggested methods for implementing these steps using standard applications programs are presented. The computer programs used to generate and display the test patterns and to estimate spatial resolution are described and are available from Defense Technical Information Center (DTIC).

9. Lindholm J.M. & Caufield K.J. (2005). Summary of live flight ground-target acquisition data (*Warfighter-Contract Technical Memorandum,* **24-10).** Mesa, AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

In order to improve the training capabilities of flight simulators, the Air Force Research Laboratory (AFRL) is currently supporting the development of an ultra-high resolution flight-simulator visual system. Here we review available literature on out-the-window ground-target acquisition. The results of these studies can be used to assess whether the new ultra-high resolution visual system is able to support air-to-ground training at realistic distances.

10. Lindholm, J.M. & Lerman, D.J. (2004). Network transport delay: Kinematic analyses, perceptual research, and task performance evaluation (*Warfighter-Contract Technical Memorandum 24-07*). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

Network data transmission is limited by the speed of light. However, transmission time is likely to be significantly longer than the theoretical minimum. Moreover, because networks have limited bandwidths, data packets are typically sent relatively infrequently during DMO: Unless a rotational- or positional-discrepancy (e.g., difference between ownship true position and ownship dead-reckoned position) threshold is exceeded, packets are sent in accord with a “heartbeat” (e.g., once every five seconds). For a given ownship discrepancy, predict-ahead algorithms and type of time stamping affect the discrepancies registered on the receiving end, while the training task, smoothing (discrepancy-correction) algorithms, and numerous image parameters—including aircraft image size, contrast, and velocity; basic IG (e.g., spatial resolution, antialiasing-filter) and display (spatial resolution and pixel response time) properties—presumably affect the perceptual and training effects of the registered discrepancy (or sequence of discrepancies). Here we propose to combine kinematic analyses, perceptual research, and performance evaluation to assess effects of network transport delay. The results should allow us to identify conditions and tasks for which discrepancies are likely to be perceptible and to suggest thresholds and smoothing algorithms that would minimize visible artifacts and support task performance. When network latency data become available, the integrated data should help answer a variety of questions regarding networked simulation.

11. Lindholm, J. & Kershner, J. (2004). DEEP: A demonstration, evaluation, and experimentation package (*Warfighter-Contract Technical Memorandum 24-08*). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

We are developing a software package to support demonstration, evaluation, and experimentation concerned with effects of various PC graphics options on flight simulator imagery. This document is meant to serve as a user’s manual for the first version of this package.

12. Lindholm, J.M., Scharine A.A., & Pierce, B.J. (2003). Next-generation flight simulators: Image update-rate considerations (*AFRL-HE-AZ-TR-2003-0007)*. Mesa, AZ: Air Force Research Laboratory, Warfighter Training Research Division.

The level of detail in flight-simulator images depends upon the resolutions of the database, the IG and the display. In response to the need for greater detail, resources are being devoted to increasing the spatial resolution of each of these system components. Next-generation flight-simulator visual systems will thus be capable of representing smaller environmental features and of representing a given feature at a greater distance. However, flight-simulator imagery is more than a sequence of static, spatial images. The visual system of a simulator creates three-dimensional space-time images, and the quality of these images depends on the temporal as well as the spatial characteristics of both the IG and the display. Here we discuss how the spatial resolutions of the database and the IG affect the temporal frequencies in an image and thus the extent of temporal aliasing likely with a standard, 60-Hz image-update rate. We also discuss how the spatial and temporal resolutions of a display system limit the spatiotemporal-frequency spectrum of the display image. We conclude with a brief description of some perceptual effects of temporal aliasing.

13. Morgan, W. (2004). Determining the on-screen image size of an object in virtual space (*Warfighter-Contract Technical Memorandum 24-06*)**.** Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

In the flight simulation systems used for pilot training, computer-based image generators (CIG) use perspective projection algorithms to generate on-screen 2-D images from databases that define 3-D virtual worlds. In the ongoing effort to improve CIG, it is often necessary to determine the size of an object's on-screen image relative to its size in the virtual world. This document is intended as a readily available source of the equations needed for these calculations and an explanation of how the equations are developed. In addition, the attached CD provides an Excel spreadsheet to automate the calculations, and example C / C++ code, which performs the calculations and can be included in software as needed.

14. Morgan, W.D. & Geri, G.A. (2005). A review of targeting pod systems and a summary of requirements for a targeting-pod simulation (*Warfighter-Contract Technical Memorandum,* **24-09).** Mesa, AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

Targeting–pod systems (TPSs) provide improved target identification, automatic target tracking, laser pointer functions, and generally more accurate weapons delivery. They have therefore become indispensable in many air-to-ground combat tasks. For this reason, it is important to simulate targeting pods in current flight-simulator training systems. We have initiated a study of how best to simulate a targeting-pod system for use by the Visual Research and Visual Development Groups at AFRL, Mesa. We begin here by briefly describing existing targeting-pod systems, and then presenting a more detailed description of the Sniper XR targeting pod, which appears to be the current system of choice for the U. S. Air Force. A targeting-pod simulation system developed by L-3 Communications has been chosen as the initial system for evaluation, and so we summarize databases and run-time system requirements for that system.

15. Morgan, W., Goodyear, M., & Geri, G. (2003). A technique for measuring the filament and phosphor on-time of Barco projectors used in the Viper/M2DART. (*Warfighter-Contract Technical Memorandum 24-01).* Mesa, AZ: Air Force Research Laboratory, Warfighter Training Research Division.

A technique is described for monitoring the on-time of the Barco CRT projectors used in the Viper/M2DART at AFRL/Mesa. The time that the CRT filament is on and the time that the phosphor is activated (with high-voltage) are not necessarily the same, and they do not have the same effect on the reduction over time in the quality of displayed imagery. The technique proposed here provides independent estimates of these two times. In addition, other possible methods for estimating on-time, which may be suitable for other applications, are briefly discussed and compared with the chosen method.

16. Patterson, R (2003). Review and analysis of helmet-mounted displays for use in Air Force mission training and rehearsal. (Contractor prepared report, AF Contract F41624-97-D-5000). Mesa AZ: Air Force Research Laboratory, Warfighter Readiness Research Division.

This paper provides a review and analysis of some of the visual perceptual issues related to the use of helmet-mounted displays for mission training and rehearsal. A typical HMD system is presented, which is composed of several parts: an image generator, a display device attached to the head or helmet, relay optics, a combiner if the imagery is seen as superimposed on another display screen or superimposed on the outside world, and a head-tracking system. Next, an analysis of perceptual issues related to the use of HMDs in two specific situations is given: (a) simulation of off-bore sighting, and (b) simulation of OTW viewing. For simulation of off-bore sighting, monocular HMDs are used while the user views the display screen of a flight simulator. Here, a monochrome image source with high brightness and resolution (contrast ratio of 1.2 or greater) is recommended, as is a field of view of 4-5 degrees. The head tracker, whose sampling rate should be 120 Hz or greater, should measure the elevation and azimuth of the helmet and its temporal lag should be no greater than 16 msec. Accuracy within the head motion box should be around 2 mrad for simulation of weapon aiming to 10 mrad sufficient for launching air-to-air missiles. For simulation of OTW viewing, binocular HMDs are used. Here, a high-resolution display having a required resolution of 1-2 armin/pixel is recommended as well as a field of view greater than 40 deg. Interocular differences in luminance no greater than 30%, a rotational difference no greater than 10 arcmin, horizontal or vertical differences in image size no greater than 1.5%, and deviation between centers of the two displays no greater than 0.18 prism diopters (6.12 arcmin), are recommended. The update lag between head movements and update of display imagery should be less than 40 sec. Finally, recommendations for future research projects are given, e.g., depth of focus. In simulating off-bore sighting using a monocular HMD worn in a flight simulator, the plane of focus of the symbology on the HMD should match the viewing distance to the display screen of the simulator so that all images are in focus. However, when making a head movement and directing gaze to a point at some eccentricity, the viewing distance to the display screen will be slightly greater than the plane of focus of the reticle, and as a result, one or both set of images will be out of focus. This raises the question of how can display brightness and contrast be used to maintain a large depth of focus.

17. Pierce, B.J. & Geri, G.A. (2003) Perceptual and engineering evaluation of high-fidelity flight simulator visual displays. *AFRL Technology Horizons*, *4*, 39-41.

This investigation was an engineering evaluation of display spatial resolution and a perceptual study of the simulated range where observers could recognize aircraft aspect angle. Researchers compared the engineering and perceptual data to determine the relationship between the measured display spatial resolution and perceptual performance of high-fidelity flight simulator visual displays.

18. Winterbottom, M. D., Patterson, R., & Pierce, B. J. (2005). Review and Analysis of Helmet-Mounted Displays for use in Air Force Training and Simulation. AFRL-HE-AZ-TR-2005-0186.

This report provides a review and analysis of the published literature on head-mounted displays (HMDs). In doing so, this report also draws heavily from the basic vision research literature in order to help provide insight for future design solutions for HMDs. In particular, we discuss several key perceptual issues that are relevant to the use of HMDs. The issues discussed are: (1) brightness and contrast; (2) accommodation- vergence synergy; (3) field of view; (4) binocular input; and (5) head movements. This review of the literature is intended to anticipate and solve perceptual issues associated with two particular HMD applications:

(1) simulation of off-bore sight (OBS) targeting and (2) full field-of-view out-the-window (OTW) simulation for deployable flight training. Additionally, several technology issues important to the continued development of HMDs are discussed. This report concludes with a set of recommendations for the design and use of HMDs for OBS and OTW flight training applications.

Perceptual-Research Project Summaries

Summarized here in greater detail are seven research projects, some of which have been described earlier, and some of which were begun in previous reporting periods but completed in the past two years. The titles of the projects are:

I. Low-Altitude Flight Performance as a Measure of Flight-Simulator Capabilities

II. Individual Differences in Speed Maintenance in Low-Altitude Flight

III. Accuracy of Heading Performance in Low-Altitude Flight

IV. Effects of Image Generator Resolution on Perceived Motion Quality

V. Evaluation of Target-Aircraft Aspect-Angle Discrimination in an Operational Flight Simulator

VI. Deep: A Demonstration, Evaluation, and Experimentation Package

VII. Integrated Assessment of the Spatial and Temporal Resolution of Flight-Simulator Displays

I. Low-Altitude Flight Performance as a Measure of Flight-Simulator Capabilities

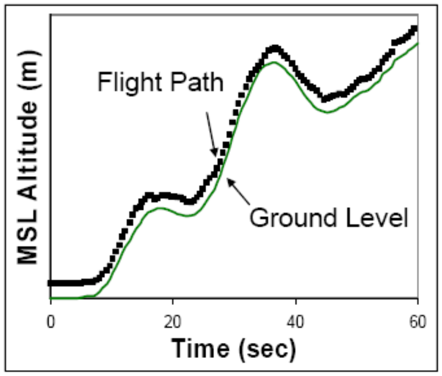

Figure 1

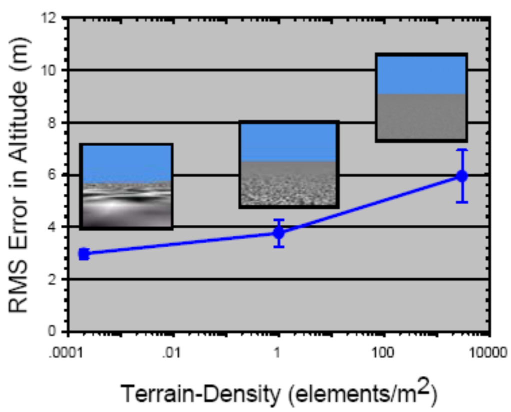

Figure 2

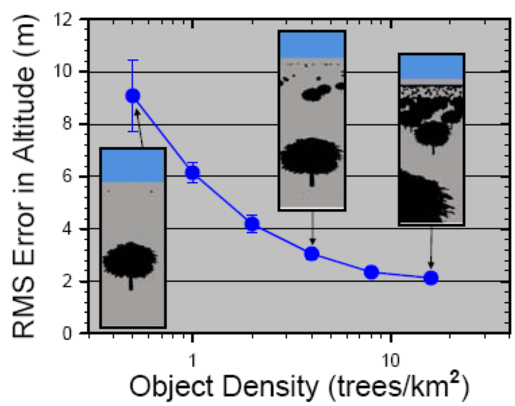

Figure 3

Payoff

We have determined experimentally that varying two seemingly related simulated-image characteristics, namely terrain-texture density and 3-D object density, can have opposite effects on performance in a flight simulator. For terrain-texture density, simulating more than about 10^{-4} elements per square meter does not improve performance in altitude maintenance when using a typical CRT-based display system. In the case of object density, the data show that there is very little improvement in performance beyond about 8 objects per square kilometer. These terrain-texture and object density data can be used to specify the effective useful limits of image detail required for flight-simulator tasks that are dependent on ground-based visual cues.

Accomplishment

Experimental techniques have been developed to estimate the RMS error in altitude maintenance as observers flew over a series of simulated hills and valleys (see Figure 1). As the density of the terrain texture was increased, RMS error increased (see Figure 2) despite the added spatial detail in the scene. This result clearly shows the deleterious effects of insufficient display resolution on the simulation of highly detailed terrain textures. Specifically, it was found that increasing terrain-texture density resulted in a decrease in image contrast which in turn degraded performance. In the case of 3-D objects, which are typically on a larger sale than terrain texture element, increased density was not associated with a significant decrease in contrast. In this case altitude maintenance performance improved (i.e., RMS error decreased) as density was increased (see Figure 3). The data further indicate that performance does not improve substantially beyond about 8-10 objects/km^2. The terrain-texture density and 3-D object density results taken together indicate that display resolution should be measured and considered when deciding whether a given flight task can be adequately trained on a given simulator system.

Papers describing this work have been presented at the annual meetings of the *Visual Sciences Society (2004),* the *Society for Information Display* (2003), the *Association for Research in Vision and Ophthalmology (2002),* the *European Conference on Visual Perception (2002),* and the *Human Factors and Ergonomics Society (2001).*

Background

It is generally accepted that visual performance in a flight simulator will improve as the amount of displayed image detail is increased. However, the bandwidth of most operational flight-simulator displays is often relatively low. It is important, therefore, to consider the characteristics of the displayed imagery in order to determine whether sufficient image detail can be displayed to meet a specified level of flight performance. For instance, displaying the gradations in contrast typical of high-density terrain-textures is much more dependent on display resolution than is the display of the relatively few and disparate contrast variations typical of 3-D objects. Thus, limited display resolution would be expected that cues relevant to low-altitude flight tasks would be reduced more in the case of terrain-texture than in the case of 3-D objects. Previous studies of terrain texture typically used simple, high-contrast textures that could be easily produced and rendered. We have extended the results of those studies by using full grayscale textures whose spectral properties are similar to those of real-world terrains. There has also been previous work in the area of object density, but in general the data are not in a form suitable for use as a simulator specification. We have directly measured the RMS error in altitude maintenance as 3-D object density was varied using a simple and realistic flight task.

II. INDIVIDUAL DIFFERENCES IN SPEED MAINTENANCE IN LOW-ALTITUDE FLIGHT

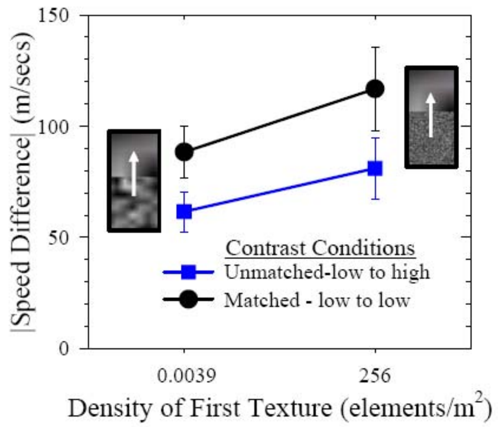

Figure 4

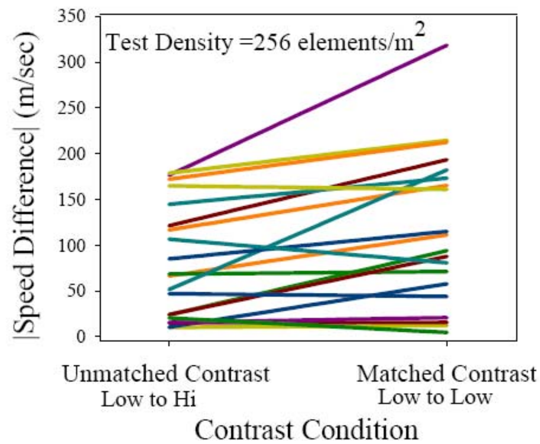

Figure 5

Payoff

It is common to have sections of a simulated database that differ in contrast, because the satellite imagery was taken in different weather conditions, or differ in density, because a designated area was built with more detail. The perception of such differences can be influenced by various cognitive factors that could in turn underlie qualitative differences in training performance. During training, it is important to point out the effect of contrast and density changes on speed perception.

Accomplishment

Experimental techniques have been developed to estimate the difference in adjusted speed, as observers flew from one density to another. In order to maintain constant perceived speed while flying from a higher-density texture to a lower-density texture, the observers increased their speed on average (see Figure 4). The magnitude of the increase in speed was greater when the contrast of the texture-densities was matched or when the density of the first texture increased. Looking at individual data, there was a large range of difference in adjusted speed (see Figure 5). Some observers made little or no adjustment in speed as they traversed the standard and test stimuli.

Papers describing this experimental work were presented at the annual meeting of the *Society for Information Display* (2003), and the *European Conference on Visual Perception (2002)*.

Background

The perception of speed through complex simulated environments is dependent both on low-level visual factors such as the rate and which objects are moving as well as higher-level cognitive factors such as known aircraft properties and previous experience in the visual environment. When there are more objects in the visual field apparently moving past the observer, most observers have the impression that they are moving faster. However, when the observer is in control of the speed of a moving vehicle, there are also cognitive factors, related to the knowledge that the observer has taken no action to change speed, that must be considered.

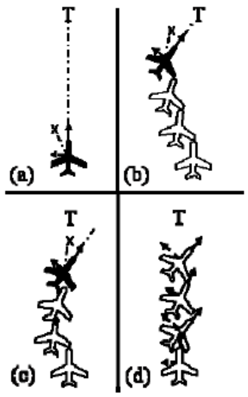

Figure 6

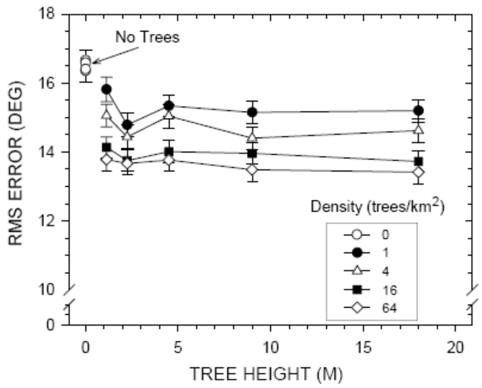

Figure 7

Payoff

The experiments described here will help to determine the minimum database content required for pilots to accurately control their direction of travel (i.e., heading) during simulated low-altitude flight. The simulation of 3-D objects is computationally expensive. Thus, simulator resources can be conserved if terrain detail can be used in place of 3-D objects to provide the visual cues required to simulate certain tasks. The present data indicate that this may be possible for the task of controlling the heading of simulated aircraft. The data also contribute to a better understanding of the basic visual processes underlying the perception of visual direction. For instance, the fact that object density affected heading performance more than did object height indicates that the relative motion of objects can be judged sufficiently well even without visual cues associated with the occlusion of farther objects by nearer ones.

Accomplishment

Experimental techniques have been developed to estimate the RMS error in heading as observers attempted to fly toward a target by the shortest path possible. The position of the aircraft was displaced by simulated wind gusts thus requiring the observer to point the aircraft in a direction different from that in which it was moving (see Figure 6). The RMS error was estimated from the difference between the actual aircraft heading and the heading corresponding to the most direct path to the target. It was determined that heading performance was significantly improved by the presence of 3-D objects (see Figure 7), and that the improvement continued as object density was increased from 1 to 64 objects per square kilometer. It was also determined that performance did not improve significantly for object heights greater than about one meter.

This research was performed in collaboration with a National Research Council Fellow who obtained a competitive research grant to work at AFRL, Mesa. A paper describing this experimental work was presented at the annual meeting of the *Society for Information Display* (2004), and two manuscripts were submitted for publication to peer-reviewed scientific journals.

Background

The research described here is part of a larger effort to evaluate the performance of simulator systems by identifying the visual cues required to perform various simulator tasks. State-of-the-art flight simulators consist of many components such as image generators, graphics cards, and display devices, each of which may limit overall performance. One visually demanding flight task that currently cannot be adequately simulated in full-field flight simulators is low-altitude flight (LAF). In addition, the system deficiencies that limit the effectiveness of LAF simulation are not well understood. In the case of heading control, the most obvious visual cue is the overall pattern of relative movement of terrain elements and/or simulated 3-D objects. Furthermore, in the case of 3-D objects, the variations in the occlusion of far objects by nearer ones during simulated flight renders their relative movement more perceptually salient. The present study was designed to investigate the relative contribution of terrain and 3-D object cues to the performance of an LAF heading task.

IV. Effects of Image Generator Resolution on Perceived Motion Quality

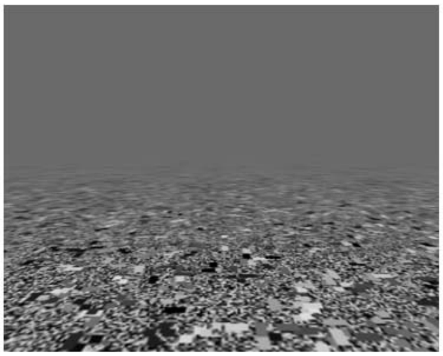

Figure 8

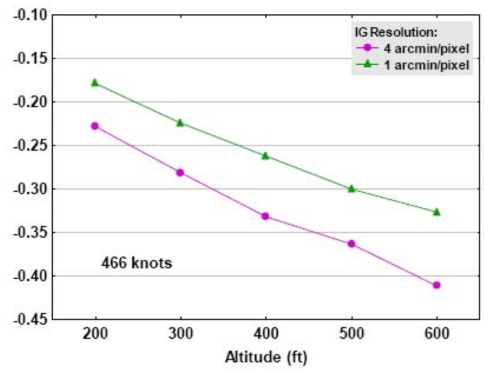

Figure 9

Payoff

To increase training capabilities and to improve image quality, AFRL/HEA is developing an ultra-high resolution flight simulator. However, there are theoretical reasons to expect that the quality of motion in simulator imagery may be adversely affected by an increase in the spatial resolution of the image generator. We have assessed the extent of poor quality motion as a function of speed and altitude for resolutions of 4 and 1 arcmin per pixel. These data can be used to identify flight tasks for which perceived motion quality may be compromised, to select textures for which motion quality will be consistently high, and to determine the image update rates needed to avoid motion artifacts for tasks that require high spatial detail during low altitude, high speed flights.

Accomplishment

We developed multiple experimental techniques for assessing the effects of IG resolution on perceived motion quality during simulated flight over flat, textured terrain (see Figure 8). With one, observers controlled the vertical coordinates of the IG's projection window in order to delimit the spatial extent (highest location within an image) of poor quality motion. The results indicate that the extent of poor quality motion increased with IG resolution and simulated speed and decreased with simulated altitude (see Figure 9). With another technique, observers controlled flight speed in order to specify the maximum speed for good quality motion and the minimum speed for poor quality motion within small windowed views of the terrain. We found that, for every view, temporal aliasing occurred for a lower speed with the higher of the two resolutions. Further analyses of the experimental data indicated that although an increase in IG resolution did result in an increase in the spatial extent of poor quality motion for a given set of flight parameters, the increase was less than the extent of temporal aliasing. This finding suggests that for most altitudes, speeds, and texture resolutions, motion quality will not be a problem with an ultra-high resolution system.

Papers describing parts of this work were presented at the Scientific Advisory Board Review (2003), published in the *Proceedings of the Interservice/Industry Training, Simulation, and Education Conference* (2003), and distributed as an AFRL Technical Report (AFRL-HE-AZ-TR-2003-0007). A second AFRL technical report is under review, an abstract was submitted for a presentation at the *Vision Sciences Society Annual Meeting* (2005), and a manuscript is being prepared for submission to a peer-reviewed scientific journal.

Background

The level of detail in flight-simulator imagery depends upon the resolutions of the database, the IG, and the display. To provide greater detail, efforts are underway to increase the spatial resolution of each of these system components. Next-generation visual systems will thus be capable of representing smaller environmental features and of representing a given feature at a greater distance. However, flight-simulator imagery is more than a sequence of static, spatial images. During simulated flight, the simulator visual system creates a three-dimensional (two dimensions of space, one of time) spacetime image that approximates the *continuous* changes in the spatial image that would result if the pilot were to actually fly through the synthetic environment. The quality of such space-time images depends upon the temporal as well as the spatial characteristics of the IG and the display. In particular, the higher the spatial detail, the higher the image update rate needed to accurately simulate continuous motion. The research reported here is part of a research program designed to investigate the interactions between database resolution, IG resolution, image update rate, and perceived ownship motion. In prior research, we have shown that, for certain flight parameters, perceived speed and perceived glide slope both increase with texture resolution.

V. Evaluation of Target-Aircraft Aspect-Angle discrimination in an operational flight simulator

Figure 10

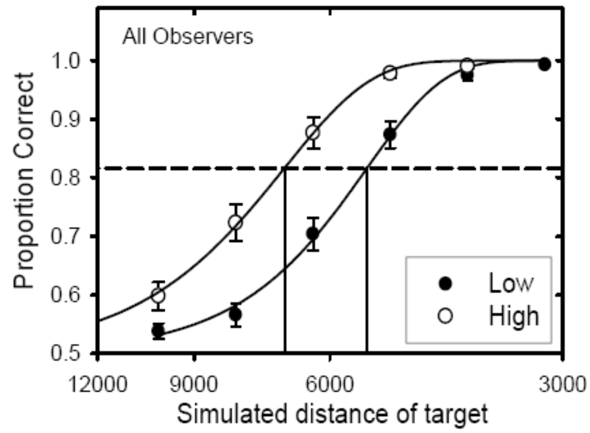

Figure 11

Payoff

Discriminating the aspect-angle (i.e., orientation) of target aircraft is a major component of many air-to-air flight tasks. We have determined the target distance at which aspect-angle can be discriminated for a CRT-based, flight simulator display system of a specified resolution. The number of displayed pixels is easy to ascertain and so is often improperly substituted for display resolution (i.e., the number of pixels that can actually be discriminated). The present data show that visual performance in a simulator correlates with measured display resolution, but not with the number of displayed pixels. These results indicate that display resolution should be measured in simulator applications that are dependent upon the discrimination of small (i.e., distant) displayed targets.

Accomplishment

We have developed an experimental procedure for directly and relatively easily assessing the discrimination of target-aircraft aspect angle. Observers were shown a single aircraft simulated directly ahead of them at various distances, and they were asked to determine whether the aircraft is headed toward their right or left (see Figure 10). Display resolution was measured using techniques that were developed at AFRL, Mesa, and which are similar to a subsequently published VESA standard. For the low-resolution display, aspect-angle discrimination reached a level of 82% correct for targets at a distance of about 6200 ft. (see Figure 11) For the high-resolution display, the equivalent discrimination range increased to about 8000 ft. No differences in discrimination range were found when the display pixel count was increased from 1280×1024 to 2048×1536 while holding resolution constant by using the same display. Thus, we have established that the commonly cited pixel-count is not a valid measure of the useful spatial detail provided by a display device.

Results of this research were published in the *Proceedings of the Society for Information Display* (2003), and submitted for publication to a peer-reviewed scientific journal.

Background

The number of pixels (or pixel-count) displayed by a projection device is easily ascertained and specified. Further, it seems intuitive that more pixels will provide a higher quality image. For these reasons, pixel-count is often used as a measure of display resolution. However, increasing pixel-count will only increase resolution if the display bandwidth is correspondingly increased. If it is not, increasing pixel-count will result in a decrease in image contrast that may actually reduce resolution. Very few studies have been done on the effects of display resolution on visual performance, and most of those evaluated display resolution by techniques that were either subjective or idiosyncratic and hence difficult to generalize. We have used a well-documented technique for measuring display resolution, which is relatively easy to perform. We have also used a direct measure of visual performance, which is based on a task that is similar to those performed in real-world flight.

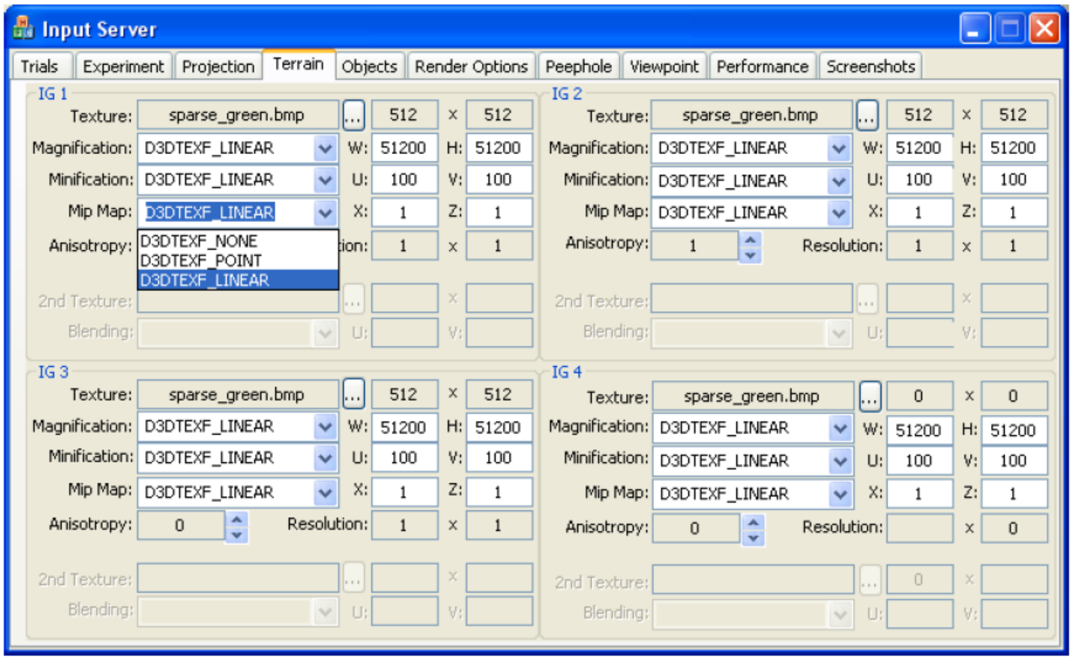

Figure 12

Payoff

Numerous vendors provide flight-simulator visual systems based on commercial-off-the-shelf (COTS) PCs and graphics cards. High-end COTS graphics cards support a wide variety of graphics rendering options that can affect image quality. With a commercial flight simulator, however, the default graphics settings may not be identified, user options may not be clearly and fully described, and load management may override the nominal settings. To assess and compare effects of rendering options, we have developed DEEP, a demonstration, evaluation, and experimentation package. DEEP also provides the means to assess effects of both database and IG resolution.

Accomplishment

DEEP includes two programs: DEEP_IG and InputServer (Figure 12). The former resides on up to four independent PCs with graphics capabilities; the latter resides on a host PC. DEEP_IG controls the image generation itself. InputServer sends database, graphics, motion, and control parameters to DEEP_IG. It also queries DEEP_IG and receives information from it regarding graphics capabilities, update rate, and viewpoint location. Finally, InputServer includes code that allows the user to design and control experiments using a very simple script language. DEEP has two operating modes: a single trial mode and an experimental mode. In the single-trial mode, which was designed to support demonstrations and evaluations, the user creates (or retrieves) a database and set of rendering and flight parameters. In the experimental mode, the user selects a previously written script file that defines the database(s) and rendering parameters for a sequence of trials, and controls the timing and data collection for one of several experimental procedures. We have used this software to evaluate different graphics cards, to compare effects of a variety of rendering options, and to conduct research that assessed effects of IG and flight parameters on image quality.

Background

There are often substantial vendor-dependent differences in the quality and content of images of a given geographical area, even when those images are generated by the same or highly similar hardware. The user, however, rarely has enough control of the graphics-card settings and database attributes to assess the bases of a particular image characteristic or the effects of the graphics and database variables themselves. DEEP was developed in response to the need for a tool that could be used to systematically vary graphics rendering options as well as database and IG resolution.

VII. Integrated Assessment of the Spatial and Temporal Resolution of Flight-Simulator Displays

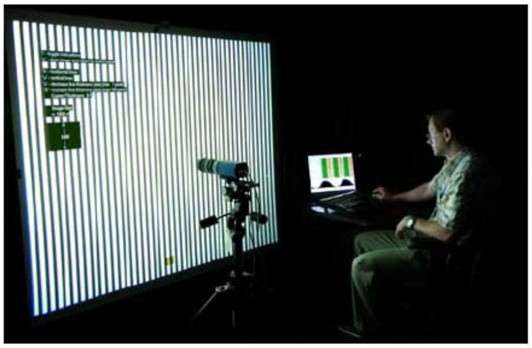

Figure 13

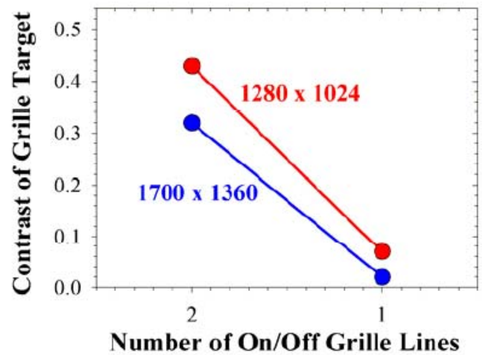

Figure 14

Payoff

Spatial and temporal resolution are fundamental and critical characteristics of the flight-simulator displays used to train Air Force pilots for a multitude of missions. Measurements of display resolution are used to assess the efficacy and limitations of flight simulators in pilot training (Figures 13 and 14). The techniques described here have also been used in the procurement of current flight simulator display systems, and in the development of next-generation, high-resolution projectors.

Accomplishment

Techniques have been developed to quickly and accurately measure the spatial and temporal resolution of flight-simulator visual displays. We have verified that the measured *spatial resolution* does not correlate well with the number of displayed pixels, which is the measure typically cited by display manufacturers and users. Further, our spatial resolution measure correlates well with performance on aircraft discrimination tasks requiring high image detail. The *temporal resolution* techniques have been used to verify that current projector systems are sufficient to display visual imagery at the update rates available from current image generators. These techniques have also been used to assess the potential trade-offs in using projectors with high spatial resolution but lower temporal resolution, as well as to make recommendations to projector manufacturer concerning improving the temporal response of their projectors.

Experiments performed to evaluate our resolution measurement techniques were presented at the annual meetings of the *American Psychological Association* (2000) and the *Association for Research in Vision and Ophthalmology* (2001), published in *AFRL Technology Horizons* (2003), and described in detail in an AFRL technical report (AFRL-HE-AZ-TR-2004-0078).

Background

The spatial resolution techniques developed at AFRL/HEA are similar to those independently developed by the VESA and published in their Flat-Panel Display Standard. There has been some reluctance on the part of display manufacturers and users to adopt the *spatial resolution* measure most relevant to flight-simulator applications. We expect that the availability of a relatively simple and intuitive technique to measure spatial resolution will address this problem. Similarly, the techniques we have developed to measure *temporal resolution* are designed for use with current flight-simulators whose projector systems can display imagery faster than it can be produced by the image generator. Resolution measurement techniques can be used to compare display systems, but they can not determine what level of resolution is required. We have therefore also developed techniques to compare measured resolution with data obtained using visual discrimination tasks typically performed on flight simulators.

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